Contribution for the roadmap of hydraulic short circuit implementation: Case of Grand-Maison pumped storage power plant

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Abstract. The objectives of the 2050 energy policy based on the decarbonization of the electric power networks generate drastic changes for grid balancing with a massive integration of non-dispatchable Renewable Energy Sources. Hydroelectric power plants already significantly support electricity power system flexibility with innovative solutions such as variable speed units, fast frequency control, fast generating to pumping modes transition, high ramping rate, inertia emulation, etc.

For pumped storage power plants (PSP), a quick solution to increase the flexibility without large investment is to operate the power plant in hydraulic short circuit (HSC) mode. This technological solution is simple to implement, but requires an in-depth study of various technical aspects among which the hydraulic transients of the new operating modes is of high importance from the installation's safety perspective. In the framework of XFLEX HYDRO H2020 European research project, the exploitation of this solution is under implementation at Grand-Maison PSP. Located in the French Alps, Grand-Maison PSP is equipped with 8 reversible multi-stage Francis pump-turbines and 4 Pelton turbines, for a total installed capacity of 1800MW, thus being the largest PSP in Europe and one of the major PSP in the world. The waterway includes a headrace tunnel, a headrace surge tank, 3 parallel penstocks feeding the 12 units operated under a maximum gross head of 955mWC.

In this paper, after a description of the general HSC considerations, the 1D model of the Grand Maison PSP and the related validation are presented. Finally, the most critical load cases in HSC operation are described to identify the potential hydraulic transient issues, such as extreme water levels in the upstream surge tank, maximum static pressure along the pressure shaft and minimum static pressure along the tunnels. The analysis performed for Grand Maison PSP is a contribution to the roadmap for the implementation of HSC operation in pumped storage power plant and will be made available as a public deliverable of the XFLEX HYDRO H2020 European research project.

1. Introduction

On the way to the decarbonization of the electric power networks, a large increase of stochastic renewable energy production is expected to cause much higher volatility in the Europe electricity system [1]. Grid operators must constantly balance supply with demand to keep the system stable and the growing electric power production from wind and solar generation will increase the complexity of this balancing [2][3].

For the pumped storage power plants (PSP), the hydraulic short circuit (HSC) mode operates at the same time a turbine in parallel to a pump. This operating mode makes it possible to increase the ability to provide ancillary services without incurring large investments [4]. For power plants equipped with fixed speed units, this technology enables to provide the Frequency Containment Reserve (FCR) and automatic Frequency Restoration Reserve (aFRR) ancillary services (corresponding to the previous primary and secondary control respectively) when operating globally in pump mode. This technology also allows to enhance manual FRR (mFRR) and Replacement Reserve (RR) ancillary services, since the input power can be adjusted thanks to the turbine active power control capability. Indeed, without the HSC mode, fixed speed technology pump unit can contribute to mFRR and RR services, but only with ON/OFF active power variation capability. For hydraulic power plants equipped with variable speed units, the HSC mode allows to combine ancillary services provided by the units in pump mode with ancillary services provided by units in turbine mode.

Despite a relatively simple implementation, the HSC mode induces operating conditions that were not necessarily studied during the commissioning of the hydraulic power plant. Therefore, in order to guarantee the safety of the installation, the introduction of such new operation mode requires to perform several investigations, such as the interference between the pump and the turbine, the flow in the bifurcations or the risks of cavitation.

2. Risk inherent in the hydraulic short circuit

2.1. General HSC considerations

In order to ensure the feasibility of HSC mode for an extended period of time, different studies must be undertaken to obtain a power range without risk. This new operating mode can lead to the following issues:

1. **Hydraulic transient behavior:** An important point related to the safety of the hydraulic power plant is the verification of the hydraulic transient behavior of the units and the interactions with the hydraulic circuit occurring in case of normal, quick or emergency shutdown and this for normal, exceptional and accidental operating load cases. In case of ternary units, complex interactions may appear between the pump and the turbine on the same shaft line. With a 1D numerical model, different load cases can be simulated to identify the potential hydraulic transient issues, such as extreme water levels in the surge tanks, maximum static pressure along the pressure shaft and minimum static pressure along the waterways.
2. **Flow in bifurcation:** With a new HSC operating mode, the flow paths in the waterways of the power plant are different compared to the pump and turbine modes. CFD studies are therefore carried out to assess the risk of hydraulic instabilities in bifurcations or trifurcations, induced by unfavorable flow patterns, such as recirculation, vortices, flow instabilities, pressure fluctuations, cavitation or vibrations in bifurcation structures [5], [6], [7], [8].
3. **Performance of the hydraulic machines:** The possible flow disturbances induced by the junctions could alter the flow pattern at the turbine and/or pump inlet, which could lead to vibrations, cavitation or a reduction in efficiency. With site measurements, a fingerprint of the unit can be obtained in normal operating mode and HSC mode. A

comparison of these experimental data allows to determine the influence of flow disturbances on the unit performances and dynamic behavior.

4. **Cavitation of the pump:** The majority of the units operating in HSC mode use the turbined flow for the pump. In the case of Pelton turbine, the aeration of the turbined water is likely to modify the cavitation behavior of the pump. An experimental campaign on a reduced scale model allows to verify this phenomenon [9].
5. **Heating of the water:** The HSC mode can also induce water heating if the pump flow is equal to the turbine flow and the turbine flow is directly pumped.
6. **Interference between the units:** The pump trip or the turbine trip can prevent the normal operation of the other units in the same pressure shaft [10]. With a 1D numerical model, the impact of the transient behavior of a hydraulic machine on the other units can be investigated.

2.2. Specific HSC considerations for Grand Maison PSP

According to the above list of possible issues, some of these points are not necessarily relevant depending on the hydraulic layout. In the framework of XFLEX HYDRO H2020 European research project, the exploitation of the HSC mode is under implementation at Grand-Maison PSP. This PSP is equipped with 8 reversible multi-stage Francis pump-turbines and 4 Pelton turbines, for a total installed capacity of 1800MW. These units are distributed over 3 pressure shafts as shown in Figure 1.

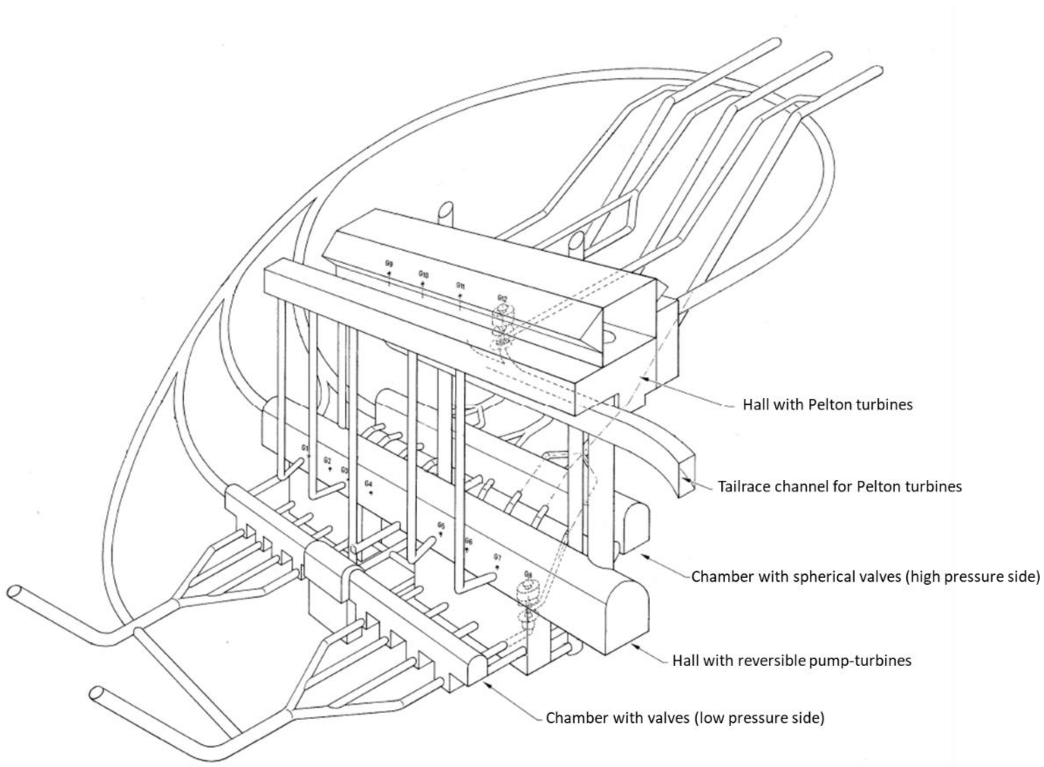


Figure 1. Isometric view of the Grand-Maison Pumped Storage Power plant caverns.

The possible impact of HSC operation at Grand Maison are as follows:

1. **For the flow in bifurcation**, according the hydraulic scheme of the power plant, four junctions were identified for CFD investigations. One junction is the trifurcation at the end of the headrace tunnel that then splits in three pressure shafts. The three other junctions are located on each pressure shaft and separate the pipes towards the Pelton

powerhouse from pipes towards the reversible pump-turbine powerhouse. The losses in the junction represent less than 0.5% of the head and no unsteady phenomena has been observed. In addition, the number of pump-turbines and Pelton turbines that operate in the HSC mode has no influence on the dimensionless head-loss coefficients [11].

2. **For the performance of the hydraulic machines**, the flow disturbances induced by the junctions do not affect the flow pattern at the injectors inlet because the junctions are located more than 120m upstream of the Pelton turbine (corresponding to more than 53 diameters distance). General Electric (GE) and EDF performed site measurement campaign including active power, pressure fluctuations and vibration to establish a fingerprint of the units and to compare HSC mode with normal turbine and pump operations. There is no experimental evidence of vibrations or a reduction in efficiency induced by this new operating mode.
3. **For the cavitation of the pump**, the flow at the Pelton turbine outlet goes through a separate tailrace channel directly to the lower reservoir and therefore the aeration of the turbined water cannot deteriorate the behavior of the pump. The advantage of having separate tailrace channels between the pump and the turbine is very beneficial for this type of operation.
4. **For the hydraulic transient behavior**, the most critical load cases are defined in the chapter 5. For each load case, the pressures along the waterway, as well as the water level in the upstream surge tank were analyzed to highlight the operating limits associated with an HSC mode [12].
5. **For the interference between units**, the pump trip induces a head variation for the other units on the same pressure shaft and therefore an almost instantaneous drop of the power of the Pelton unit. This phenomenon, named *falaise effect*, will be analyzed in detail in the chapter 5.

3. Modelling of the Grand Maison PSP

To investigate the hydraulic transient behavior of the HSC mode, a 1D SIMSEN model was created and validated with experimental data. This numerical model includes a 7000m long headrace tunnel, a differential upstream surge tank, as well as 3 pressure shafts feeding the twelve units, height reversible pump-turbines G1 to G8 and four Pelton turbines G9 to G12, see Figure 2. The main characteristics of the twelve units are defined in the Table 1. It is important to underline that in this study, the new Pelton runner with an upgrade of +10% of the rated power have been considered to analyse the future equipment of the PSP.

Table 1. Grand Maison hydraulic features.

Head	Min 820 mWC; Rated 918 mWC; Max 955 mWC	
Type of turbine	Pelton turbine with 5 injectors	Reversible Francis pump-turbine (4 stages)
Number of units: **pressure shaft #1** **pressure shaft #2** **pressure shaft #3**	 1 Pelton turbine 2 Pelton turbines 1 Pelton turbine	 3 pump-turbines 2 pump-turbines 3 pump-turbines
Rated rotational speed	428 min^{-1}	600 min^{-1}
Rated mechanical power	156 MW (upgrade in process to 170 MW)	156 MW

The upstream surge tank is characterized by a vertical shaft of 185 m height and an internal diameter of 10 m. The upper expansion chamber is differential and provides a cross section area of 1640 m^2. A special attention was paid to the spherical valves and its service seal for each unit. The modelling of this hydraulic element is realized with two valves in parallel, parameterized by the characteristic curve provided by the manufacturer. The characteristic curves of the pump-turbines and the Pelton turbines are also provided by the manufacturer and implemented in the SIMSEN model.

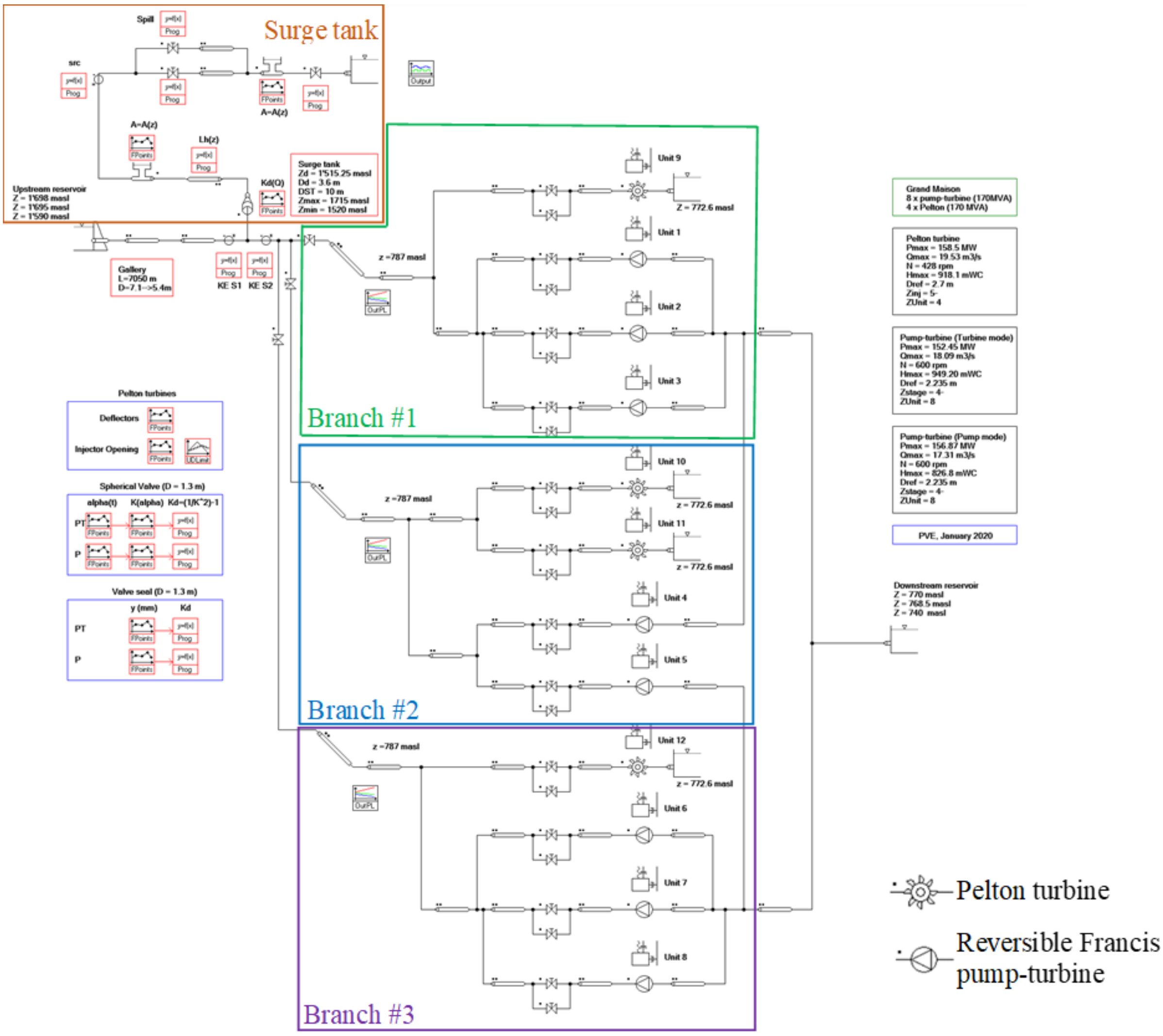


Figure 2. SIMSEN model of the Grand Maison pumped storage power plant.

4. Validation of the 1D numerical model

To validate the 1D SIMSEN model, several comparisons with experimental data were performed. In this paper, only the four following load cases are illustrated:

- *Start and Quick shutdown (QSD) of the Pelton turbine G9*. The other units were at standstill. The time history of the piezometric head at the high-pressure side of the spherical valve of the Pelton turbine is presented in Figure 3. This very good agreement between the experimental data (blue line) and the simulation results (red line) validates the dynamic behavior of the pressure shafts and the Pelton turbine discharge characteristic.
- *ESD of the 8 pump-turbines in turbine mode*. The 4 Pelton turbines were not in operation. With this load case, the transient behavior of the headrace tunnel and surge tank water level in the SIMSEN model (red line) are validated, see Figure 4.

- *Emergency shutdown (ESD) of the pump-turbine G1 in turbine mode*. The Figure 5 (left) illustrates the comparison of the transient behavior of the unit G1 between the experimental data (solid lines) and the numerical results (dashed lines). A very good reproduction of the static pressure at the inlet and outlet of the pump-turbine, as well as of the rotational speed allows to validate the 1D numerical model of the pump-turbine in turbine mode.
- *Emergency shutdown (ESD) of the pump-turbine G1 in pump mode*. The Figure 5 (right) compares the simulation results (dashed lines) with the measurements (solid lines). A very good agreement for the rotational speed allows to validate the transient behavior of the pump-turbine in pump mode.

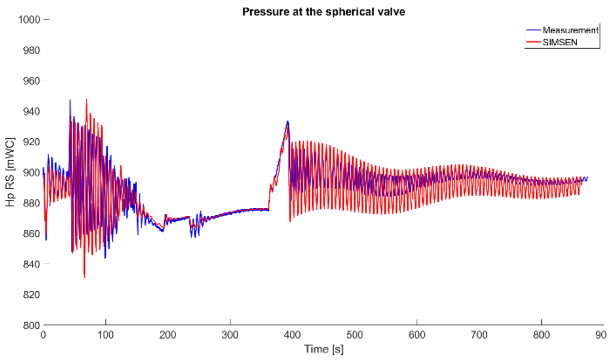


Figure 3. Start and QSD of the Pelton unit G9. Time history of the piezometric pressure at the turbine inlet, experimental data in blue and SIMSEN simulation results in red.

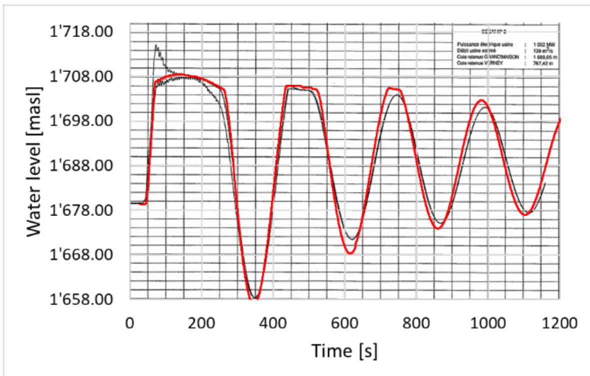


Figure 4. ESD of the 8 pump-turbines. Time history of the water level in the surge tank, experimental data in black and SIMSEN simulation results in red.

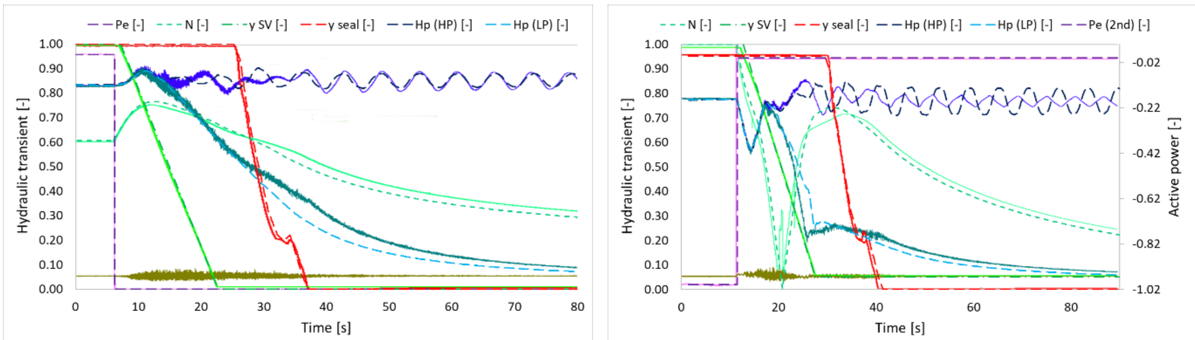


Figure 5. ESD of the pump-turbine G1 in turbine mode (left) and in pump mode (right). The experimental data are in solid line and SIMSEN simulation results in dashed line. Pm=active power, N=rotational speed, y SV=opening of the spherical valve, y seal=opening of the seal, Hp=static pressure at low pressure side (LV) or high pressure side (HP).

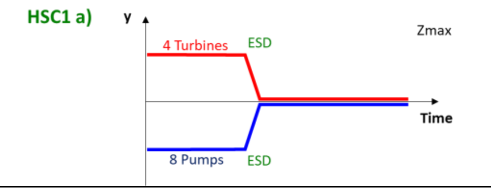
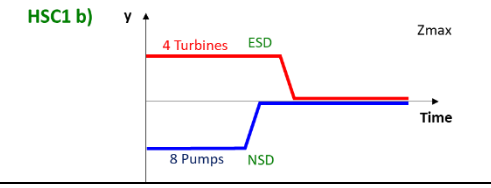
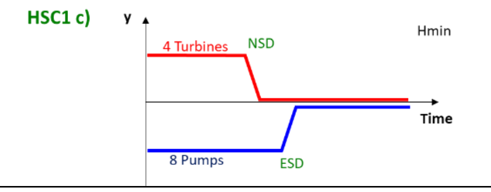
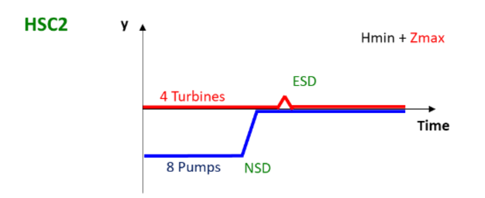
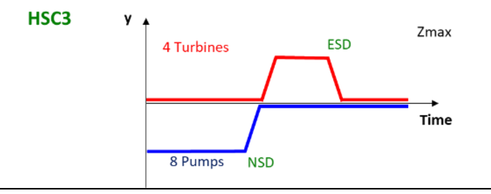
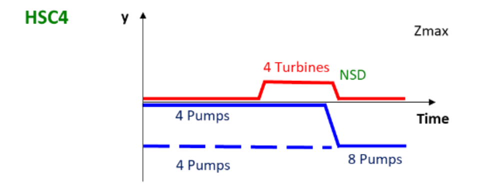
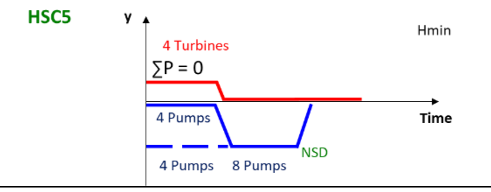
Finally, the different load cases simulated have made it possible to validate the various elements of the SIMSEN model. It is now possible to analyze the most critical load cases in order to identify possible operating limits for the HSC mode.

5. List of the critical load cases

In this study focused on the HSC operation, the load cases were limited to the sequence of two different events, see Table 1. A sequence containing a larger number of events is considered significantly more unlikely. First, the load cases are voluntarily simplified with simultaneous shutdown events for all Pelton turbines and pump-turbines in order to identify the critical cases more easily. Then, the real operating constraints of the PSP are applied to verify if the load case is still critical and if operating limitations should be applied. For each load case, a description of the sequence of events, as well as the goal are defined for the following specific operating conditions:

- ***Zmax*:** Maximum water level in the upstream and downstream reservoirs. This water level condition allows for a maximum level in the upstream surge tank in transient conditions and a maximum total flow in the headrace tunnel.
- ***Hmin*:** Minimum water level in the upstream reservoir and maximum water level in the downstream reservoir. This water level condition allows for a minimum level in the upstream surge tank in transient condition and the maximum flow in the headrace tunnel.

Table 2. Description of the most critical load cases in HSC mode, where the *y* corresponds to the flow control device position.

HSC1a)		**Description:** ESD of the 4 Pelton turbines + ESD of the 8 pump-turbines in pump mode at the worst moment for the maximum pressure in the penstock at *Zmax*. **Goal:** Maximum pressure in the penstock
HSC1b)		**Description:** NSD of the 8 pump-turbines + ESD of the 4 Pelton turbines at the worst moment for the maximum water level in the surge tank at *Zmax*. **Goal:** Maximum water level in the surge tank
HSC1c)		**Description:** NSD of the 4 Pelton turbines + ESD of the 8 pump-turbines at the worst moment for the minimum water level in the surge tank at *Hmin*. **Goal:** Minimum water level in the surge tank
HSC2)		**Description:** NSD of the 8 pump-turbines + Peak of Michaud for the 4 Pelton turbines at the worst moment for the minimum/maximum pressure in the gallery at a) *Hmin*/ b) *Zmax*. **Goal:** a) Minimum pressure in the gallery b) Maximum pressure in the penstock
HSC3)		**Description:** NSD of the 8 pump-turbines + Loading of the 4 Pelton turbines at the worst moment for the maximum water level in the surge tank at *Zmax*. **Goal:** Maximum water level in the surge tank
HSC4)		**Description:** Start of the 4 Pelton + 4 pump-turbines and NSD for the Pelton at the worst moment for the maximum water level in the surge tank at *Zmax*. **Goal:** Maximum water level in the surge tank
HSC5)		**Description:** Start of the 4 pump-turbines with 4 turbines + NSD of the pump-turbine at the worst moment for the minimum water level in the surge tank at *Hmin*. **Goal:** Minimum water level in the surge tank

Among these different load cases, the 3 most critical ones for the Grand Maison PSP have been selected and are described in the next sections.

For the load case HSC1c, the Normal Shutdown (NSD) of the 4 Pelton turbines operated at maximal power are simulated, followed by an ESD of the 8 pump-turbines at the worst moment for the minimum water level in the surge tank at minimum head. The transient behavior of the pump-turbine G1 in pump mode is illustrated in Figure 6. A negative static pressure of - 2.06mWC was detected in the headrace tunnel, close to the upstream surge tank, see Figure 7. To solve this problem, the PSP will not be operated in HSC mode when the water levels in the upstream reservoir is at minimum water level.

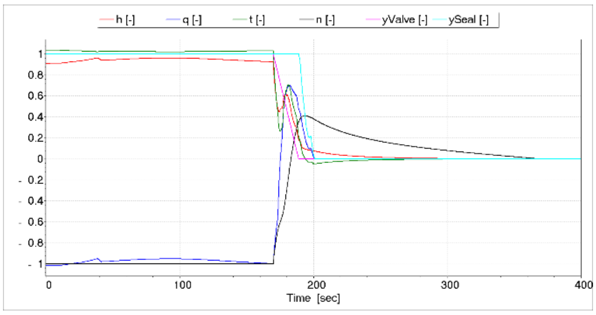


Figure 6. Time histories of the Unit G1 transient behavior after an ESD at 170s. The head (red line), the discharge (blue line), the torque (green line), the rotational speed (black line), the spherical valve (pink and light blue lines)

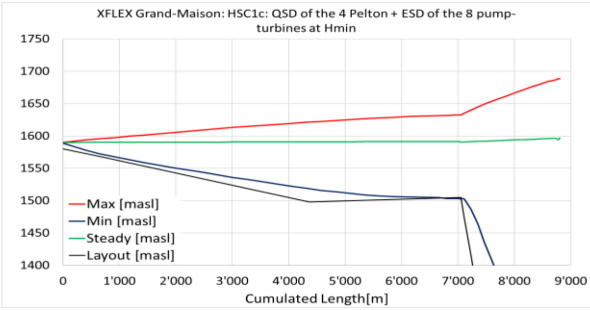


Figure 7. Pressure envelopes along the waterways. The maximum (red line), the minimum (blue line) and the steady piezometric pressure (green line). The pipe elevation (black line).

For the load case HSC2b, the simultaneous NSD of the 8 pump-turbines in pump mode are simulated, followed by the simultaneous 4 Pelton turbines startup sequence at the worst moment for the maximum pressure in the pressure shaft. An ESD occurs during the penstock reflection time, see Figure 9. The penstock reflection time is the time for the pressure wave to travel from the hydraulic unit to the nearest upstream free water surface and back. This sequence showed a maximum static pressure at turbine inlet of 117.6 bar which is above the guarantee pressure of 113.5 bar, see Figure 8. In practice, this load case is not critical because the 8 pump-turbines cannot be stopped simultaneously, but a time delay of 25s is imposed between each NSD. Therefore, the static pressure amplitude is much lower than the admissible pressure.

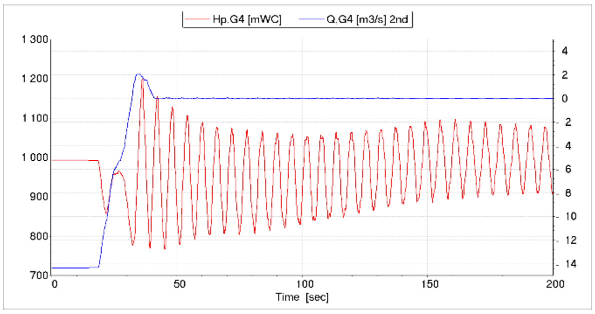


Figure 8. Time histories of the static pressure at the spheric valve inlet of pump-turbine G4 (red line) and the corresponding discharge (blue line).

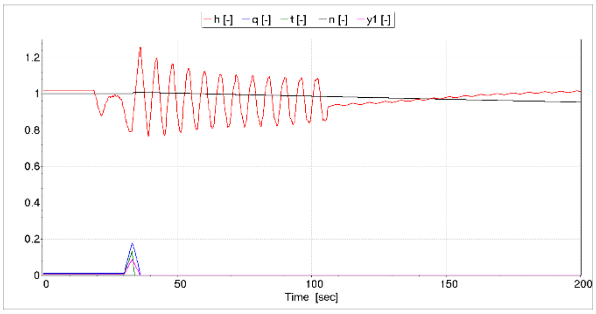


Figure 9. Time histories of the transient behavior of the Pelton turbine G10 during a peak of Michaud.

For the load case HSC5, 4 pump-turbines are still in operation at *Hmin*. The other 4 pump-turbines are started thanks to the 4 Pelton turbines connected electrically to perform a back-to-back startup sequence and reach their synchronization rotational speed. At the worst moment for the minimum water level in the upstream surge tank, the NSD of the 8 pump-turbines in pump mode occurs. The resulting water level in the surge tank is illustrated in Figure 10 and reaches a minimum value of 1519.5masl, which is -2.5mWC below the diaphragm elevation, see Figure 11. To solve this problem, the HSC mode is not allowed for the lowest water levels in the upstream reservoir.

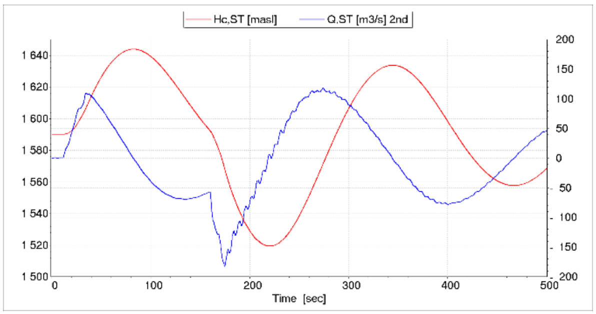


Figure 10. Time histories of the water level (red line) and the corresponding discharge for the upstream surge tank (blue line).

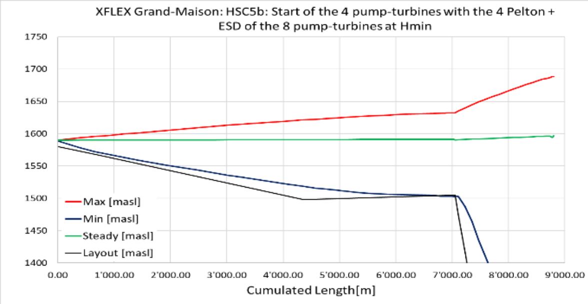


Figure 11. Pressure envelopes along the waterways. The maximum (red line), the minimum (blue line) and the steady piezometric pressure (green line). The pipe elevation (black line).

Finally, in addition to the critical load cases presented in Table 2, another phenomenon related to the active power produced by the Pelton turbine has been highlighted. *For an ESD of the pump-turbine*, a pressure drop for the Pelton unit connected to the same pressure shaft has be measured during site tests. This strong head variation induces an almost instantaneous drop of the power of the Pelton unit before returning to its initial value after 5 to 10 seconds, see Figure 12. Below a given head for a high opening of the injectors, a strong variation of torque is observed, see Figure 13. This particularity named *Falaise effect* has also been observed with the numerical model during an ESD of a pump-turbine in pump mode at *Hmin* or during a simultaneous ESD of several pump-turbines in pump mode whatever the water level in the upstream reservoir [13]. As an ESD cannot be intrinsically anticipated, EDF deployed counter measures to detect Pelton runner loss of efficiency and recover turbine power in accordance with injector opening.

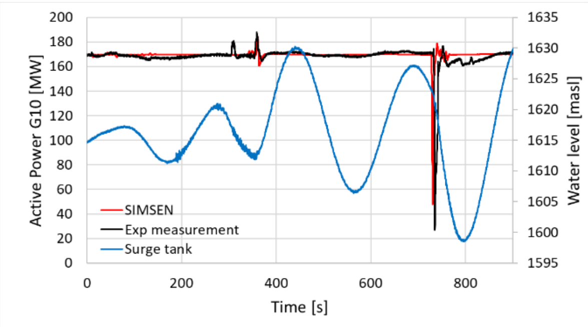


Figure 12. Time histories of the active power from experimental data (black line), from SIMSEN model (red line) and the water level in the surge tank (blue line).

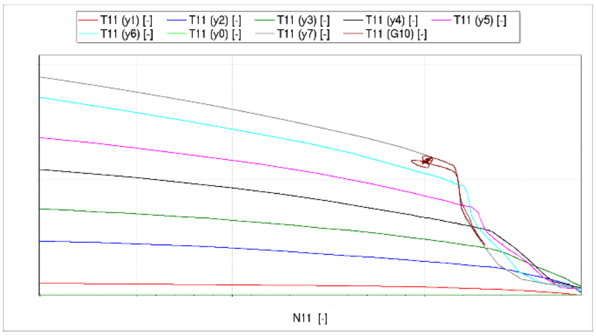


Figure 13. Characteristic curve of the Pelton turbine G10. In brown, transient behavior of the adimensional torque T11 as function of the adimensional rotational speed N11.

6. Conclusion

In order to increase the power system flexibility, the pumped storage power plants (PSP) can be operated in hydraulic short circuit (HSC) mode without incurring large investments. Despite a relatively simple implementation, the HSC mode requires to perform several investigations, such as the interaction between the pump and the turbine, the flow in bifurcations or the risks of cavitation. A list of the inherent risk was proposed in this paper and was applied to the Grand Maison PSP.

After a validation of the 1D SIMSEN hydraulic model of the Grand Maison PSP, the most critical load cases were presented in order to highlight the different operating limits for a new HSC mode. To solve the problem of minimum water level in the upstream surge tank and minimum static pressure in the headrace tunnel, the HSC mode is not allowed for the minimum water level in the upstream reservoir. Because of the specific characteristic curve of the Pelton turbine, the falaise effect may appear after an ESD of the pump-turbine operating in pump mode and in the same pressure shaft. It is important to note that the load cases studied in this paper are specific to Grand Maison PSP and that the list may be quite different for another hydraulic power plant.

Finally, this analysis performed for Grand Maison PSP is a contribution to the roadmap for the implementation of HSC operation and will be made available in the public deliverable of the XFLEX HYDRO H2020 European research project. This document will be a powerful communication tool to promote and highlight the flexibility gain that the different technologies addressed in the XFLEX HYDRO can bring to hydroelectric power plant operators.

7. Acknowledgments

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